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MBE GROWTH OF LARGE DIAMETER InP-BASED LATTICE-MATCHED AND METAMORPHIC HBTS

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InAlAs/InGaAs/InP heterojunction bipolar transistor (HBT) structures were grown lattice-matched on InP substrates and metamorphically on GaAs substrates by molecular beam epitaxy. Generic structures with a thin base of 500 Å and doped at 4×10^{19} cm^{-3} were chosen to support the frequency response required for advanced wireless and fiber-optic telecommunication products. Beryllium- and carbon-doped large-area devices were found to exhibit similar DC characteristics. No significant difference in current gain or linearity was observed for metamorphic devices compared to their lattice-matched counterparts.

I. Introduction

InP-based single and double heterojunction bipolar transistors (SHBT and DHBT) are prime candidates for advanced wireless and 40 Gb/s fiber-optic telecommunication applications. HBTs with f_t of over 200 GHz were achieved by combining the superior electronic properties of InP, InGaAs, and InAlAs, a thin low resistivity base layer, and the precise control of alloy grading afforded by molecular beam epitaxy (MBE). To fully realize the potential of InP-based HBTs, a manufacturable and reliable epitaxial growth process on large diameter substrates is necessary.

The usefulness of InP-based HBTs with heavily beryllium (Be) doped base is limited by the risk of Be diffusing towards the base-emitter junction and the resulting degradation in current gain and device reliability. Devices fabricated from structures using the low-diffusivity *p*-type dopant carbon (C) frequently exhibit lower current gain [1] due to auto-compensation in the InGaAs base and C precursor transients in the growth chamber. In this work, we evaluated C- and Be-doped HBT devices in terms of DC characteristics.

The full commercialization of InP-based HBTs may be limited by the size (maximum 4" diameter), material cost per square inch, and brittleness of InP substrates currently available. To overcome these difficulties, we investigated the growth of InP-based HBTs on GaAs substrates via metamorphic buffers (M-HBTs). Comparative data on heavily C-doped HBTs grown lattice-matched on InP (LM-HBTs) and metamorphically on GaAs substrates (M-HBTs) is presented.

Both SHBTs and DHBTs were grown with InP or InGaAs collectors and with InP or InAlAs emitters. The combination of material systems was chosen to optimize breakdown voltage and etch-stop properties for device processing. Uniformity data and DC characteristics of large-area devices are discussed.

II. Experimental

All epitaxial structures were grown on Varian GEN-II and Applied Epi GEN-III MBE reactors using all solid groups III and V sources and 3" and 4" SI InP and GaAs substrates. For base doping, a standard effusion cell was used for Be, and a gas injector was used for C with CBr_4 as the precursor.

All HBT structures discussed in this work have a 500 Å InGaAs base layer doped at 4×10^{19} cm^{-3}. Bulk InGaAs layers doped with Be and C at this concentration exhibit similar carrier transport properties, with room temperature mobilities between 60 and 65 cm^2/V-s. SHBT structures have an InGaAs collector, an InP emitter and an abrupt base-emitter junction. DHBT structures have an InP collector and an InAlAs emitter layer. Digital gradings at the base-emitter and base-collector junctions were used to improve carrier injection and to suppress current blocking.

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High-resolution x-ray diffraction measurements indicate typical lattice mismatch of ≤500 ppm and maximum alloy composition variation of ~200 ppm across a 4" wafer. The typical layer thickness variation and base doping uniformity with both Be and C was ≤5%.

MHBT structures were grown on GaAs substrates with a linearly graded InAl(Ga)As buffer layer and an inverse graded step. The M-buffer design was used previously for M-HEMT growth.[2] The residual dislocation density, plastic relaxations in the buffer and surface roughness data were described elsewhere.[3,4]

Material evaluation of the HBT structures consisted of DC measurements performed on large-area devices with base-emitter junction dimensions of 110×110 μm^2.

III. Results and Discussions

1) LM-SHBTs

The Gummel plots for large-area devices obtained from our initial set of LM-SHBTs samples are shown in Fig. 1. DC parameters are summarized in Table I.

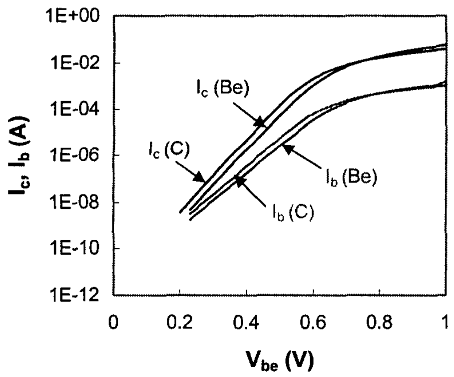

Fig. 1. Gummel plots of Be- and C-doped SHBTs.

Table I. Summary of Large-Area SHBT Device Results.

Structure	SHBT:**Be**	SHBT:**C**
Current gain, β @I_b=1.2mA	**50**	**40**
Base R_{sh} (Ω/sq) TLM	**550**	**488**
V_{offset} (V)	0.15	0.12
BV_{ceo} (V)	3.5	4.0
B-E junction V_f/V_r (V@0.5 mA)	0.577±0.014 /5.0	0.550±0.015 /4.6
B-C junction V_f/V_r (V@0.5 mA)	0.45/5.7	0.40/5.4
Ideality factors (n_c/n_b)	1.11/1.41	1.08/1.37

Both devices exhibit excellent doping uniformity as evidence by the minimal variation (<3%) in the B-E junction turn-on voltage across the wafers. For this initial set of SHBTs, we observed a slightly higher turn-on voltage of approximately 30 mV for the Be-doped devices, possibly due to slight Be diffusion towards the B-E junction. The difference in the current gain is attributed to the difference in the actual base doping concentration as reflected by the base sheet resistance (R_{sh}) values.

2) LM-DHBTs

Next, we developed the DHBT structures, focusing on suppressing Be diffusion and improving the gas manifold and injector design to reduce CBr_4 transients. By optimizing the growth procedure and hardware configuration, we narrowed the difference in current gain (50 and 45, respectively) and turn-on voltage (16 mV) between Be- and C-doped DHBTs. The resulting Gummel plots are shown in Fig. 2 and the DC characteristics are summarized in Table II.

The use of a thin InP collector layer was found to increase the device collector-emitter breakdown voltage to 10 V (Fig. 3). SIMS analysis data shown in Fig. 4 show no sign of Be diffusion.

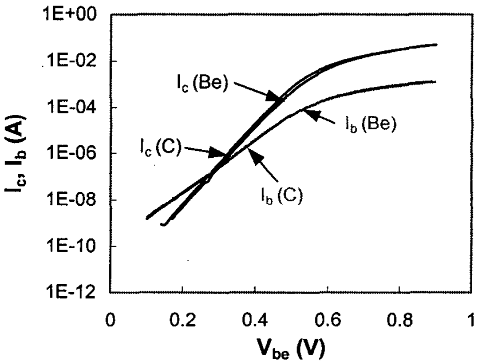

Fig. 2. Gummel plots of Be- and C-doped DHBTs.

Table II. Summary of Large-Area DHBT Device Results.

Structure	DHBT:**Be**	DHBT:**C**
Current gain, β **@I_b=1.2mA**	**50**	**45**
Base R_{sh} (Ω) TLM	**565**	**565**
V_{offset} (V)	0.07	0.07
BV_{ceo} (V)	10.0	10.0
B-E junction V_f/V_r (V@0.5 mA)	0.503±0.011 /2.2	0.519±0.003 /1.6
B-C junction V_f/V_r (V@0.5 mA)	0.50/12.5	0.40/12.0
Ideality factors (n_c/n_b)	1.00/1.41	1.00/1.43

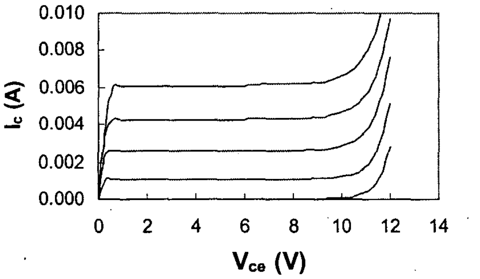

Fig. 3. Common emitter characteristics of DHBT:Be.

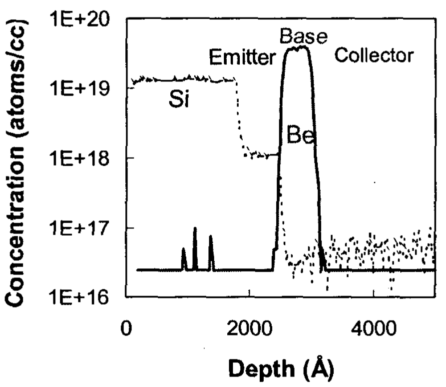

Fig. 4. SIMS doping profile for a Be-doped LM-DHBT.

3) M-SHBTs

We extended our work on lattice-matched growth of C-doped DHBT to metamorphic growth in order to take advantage of the more mature GaAs substrate technology. The design and growth procedures for the InAl(Ga)As-based M-buffers were optimized for smooth surface morphology and complete strain relaxation.[2–4]

The DC characteristics of M-HBTs, including current gain, base-emitter and base-collector ideality factors, were found to be strongly influenced by both the surface roughness and the residual dislocations in the base region. In general, the surface roughness of metamorphic epilayers scales as a function of total layer thickness. Since HBT structures are typically thicker than HEMT structures, M-HBT growth is more challenging than the corresponding M-HEMT growth. Despite the presence of dense crosshatch patterns, however, M-HBT structures grown under optimal conditions exhibit root-mean-square roughness of only 1.6 nm as measured by AFM using a scan size of 5 μm × 5 μm. This value compares very favorably with those published for M-HEMT structures and is lower than the 2.0 nm figure of merit for gauging device reliability.[2–5]

The DC characteristics of M-HBT structures were compared to that of baseline LM-HBT structures. We started with a SHBT:Be test structure consisting of a thin InGaAs collector, a 1000 Å base doped at 1×10^{19} cm^{-3} with Be, and an InAlAs emitter. Large-area device results are listed in Table III. The difference in the current gain to base sheet resistance ratio of the M-SHBT and LM-SHBT is less than 5%.

Table III. Summary of Large-Area Device Results for M-SHBT and LM-SHBT doped with Be at 1×10^{19} cm^{-3}.

Structure	**M**-SHBT:**Be** (on GaAs)	**LM**-SHBT:**Be** (on InP)
Current gain, β @I_b=1.2mA	**320**	**360**
Base R_{sh} (Ω/sq) TLM	**909**	**985**
V_{offset} (V)	0.18	0.15
BV_{ceo} (V)	3.4	4.0
B-E junction V_f/V_r (V@0.5 mA)	0.575±0.0085 /3.6	0.577±0.037 /3.8
B-C junction V_f/V_r (V@0.5 mA)	0.4/14.4	0.4/15.0
Ideality factors (n_c/n_b)	1.39/1.67	1.31/1.46

Gummel plots for the M-SHBT and LM-SHBT devices also exhibit very similar characteristics (Fig. 5). There is no indication of p-n junction degradation due to interfacial roughness or Be diffusion.

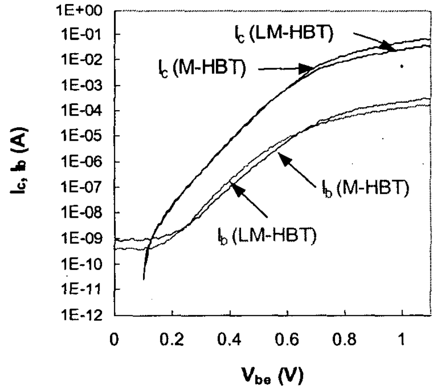

Fig. 5. Gummel plots comparing M- and LM-SHBTs.

The metamorphic growth of heavily C-doped SHBT structure is also promising. We achieved a current gain of 35 for a base sheet resistance of 486 Ω/sq. As listed in Table IV, the uniformity and

DC characteristics of M-SHBT are comparable with those of its lattice-matched counterpart (Table I).

Table IV. Summary of Large-Area Device Results for M-SHBT doped with 4×10^{19} cm^{-3} C.

Structure	**M-SHBT:C** (on GaAs)
Current gain, β @I_b=1.2mA	**35**
Base R_{sh} (Ω/sq) TLM	**486**
V_{offset} (V)	0.15
BV_{ceo} (V)	4.0
B-E junction V_f/V_r (V@0.5 mA)	0.557±/0.012 /4.2
B-C junction V_f/V_r (V@0.5 mA)	0.40/5.2
Ideality factors (n_c/n_b)	1.09/1.41

These preliminary results suggest that the metamorphic approach for HBT growth is viable for producing large diameter and potentially lower cost wafers for next generation devices.

IV. Conclusions

We have developed MBE growth processes for large diameter InP-based HBT structures, with base regions heavily doped with Be and C, that are attractive for advanced wireless and fiber-optic telecommunications applications.

Growth parameters were optimized to effectively suppress Be diffusion for a base doping level up to 4×10^{19} cm^{-3}. Both Be- and C-doped devices exhibit good linearity, DC current gain, and across-wafer uniformity. The use of an InP collector and an effective base-collector grading help increase device breakdown voltage and eliminate current blocking.

M-HBTs grown on GaAs substrates exhibit DC characteristics comparable to their LM counterparts grown on InP substrates. No significant difference in DC characteristics was observed for both Be and C-doped SHBTs. These preliminary results demonstrate the potential of M-HBT as a low cost alternative to lattice-matched devices grown on InP substrates.

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